LIGO

Imaged Scattered light from LIGO Resonant Cavities:

Micro-roughness vs Point Scatter Loss

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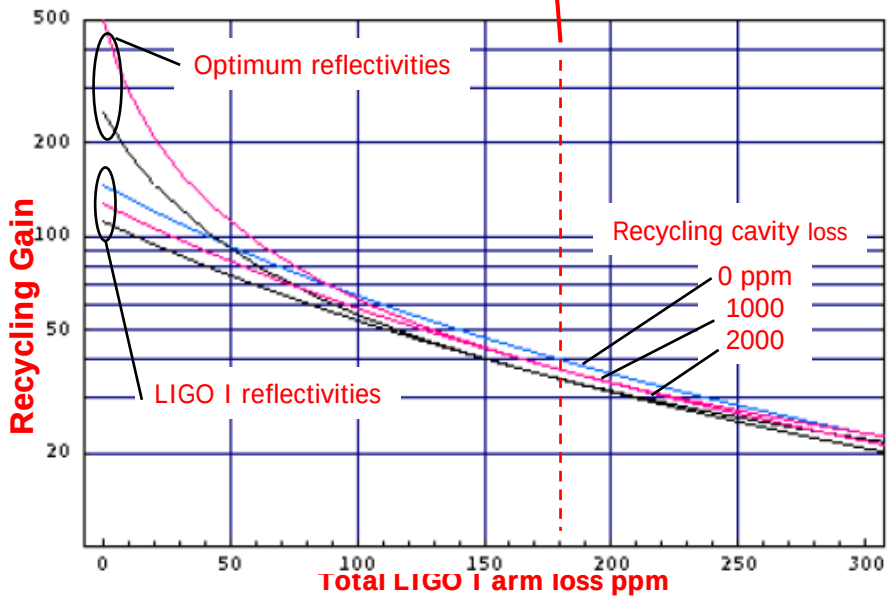
With acknowledgement of entire LIGO team for interferometer Optics development

Cavity Loss: Now ⟶ Future ?

- LIGO I cavities presently: net L_{RT} =180 ppm (excluding $T_{coupler}$)
  - » Minor portion from absorption; finite mirror diffraction; R<1.

  Strongly limits future recycling gains, or QND performance



- **Discrete cavity record: 2.7ppm**

  Rempe, Kimble, et al. Opt Lett **17,** 363 (*w*~30μm)

- **Disparity is scatter [Loss]**

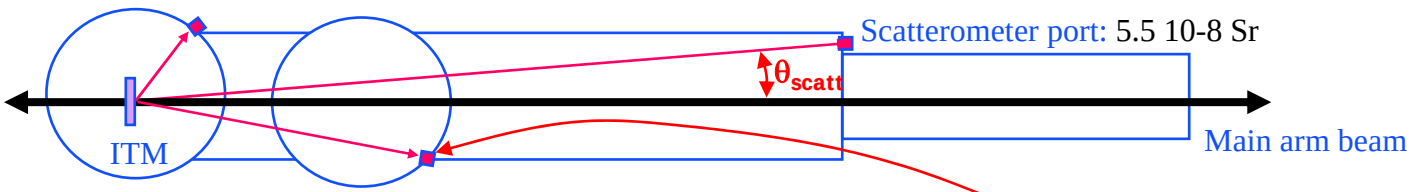
Image of cavity beam TM foot print at non-specular Observation angle (coherent, 1064nm)

Resonant arm, Gaussian illuminated ETM

Scatterometer studies

- Direct observation of the excess scatter (full operating interferom.)
  - Whence the 50-70ppm avg. additional loss per TM?

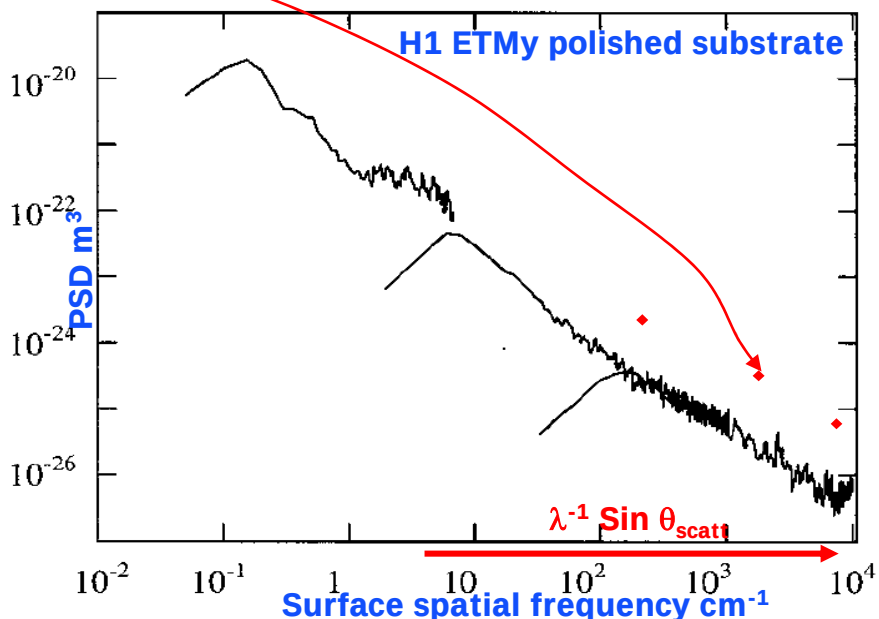
- In situ studies: Some HR surfaces viewable @ 3 angles:



- Angular dependence more isotropic, "point like" than metrology prediction
- Extrapolating to all angles consistent with net ~70 ppm/mirror loss

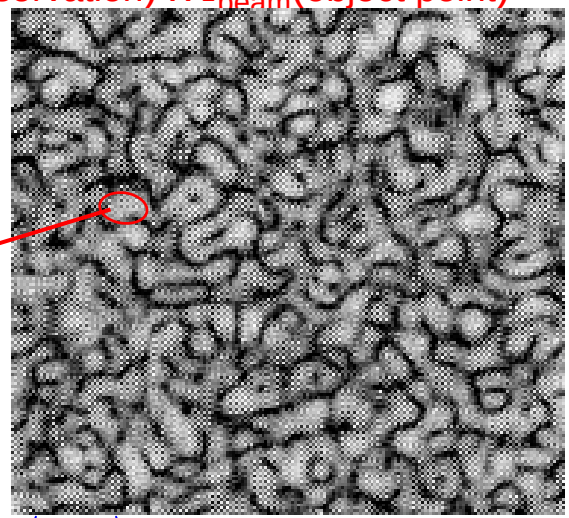
- ~same level, character for every TM independent of history/cleaning.

Is "dust" contamination ruled out ?



HR surface beam spot imaging

- What do we expect imaged scatter to look like?
  - » Gaussian micro-roughness contribution: similar to "speckle"
    - "standard" speckle theory: random, rough ($\int PSD << \lambda^2$) surface
    - Strictly non-specular (Rayleigh << observation angle)
    - Mean speckle pattern intensity = PSD(θ of observation) x I_{beam}(object point)
    - Detailed intensity pattern not fixed with respect to θ(observation)



    - "Size" (correlation) scale of speckles ~ Airy resolution length of imaging optics
    - Distribution of image intensities, $\boldsymbol{P}(I) \sim \exp(-I / \langle I_{mean} \rangle)$: I=0 most likely
  - » Discrete point (defect) contribution: Same ~Mie scatter point location, all views

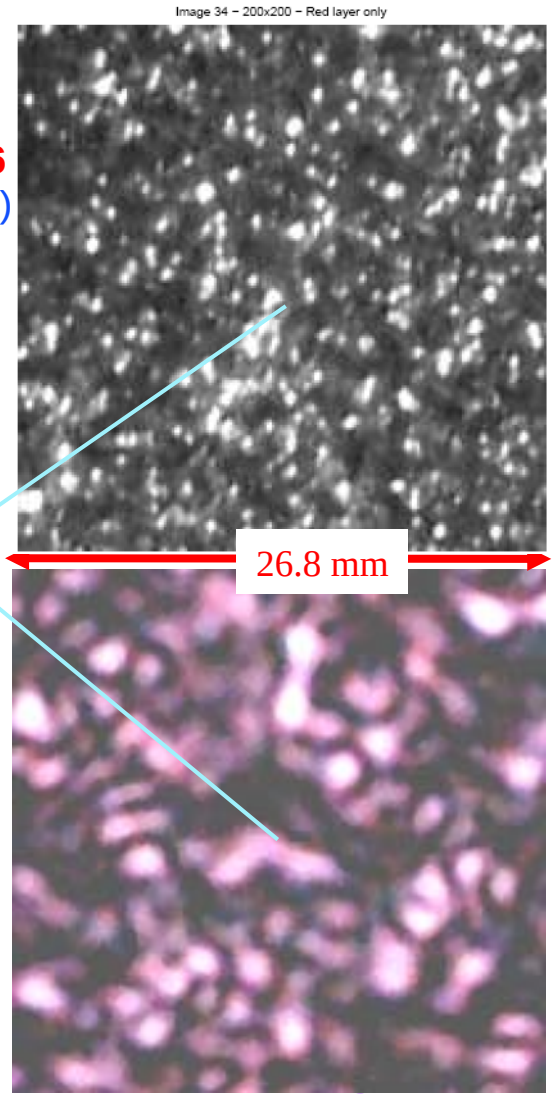
Image analysis of 2k ETMx c.7/'04

Hi quality SLR CCD images analyzed (RAW, uncompressed pixel data

f/5.6
(Airy resolution length ~ 0.4mm)

View point: ~9° from normal
5.8 m from HR surface

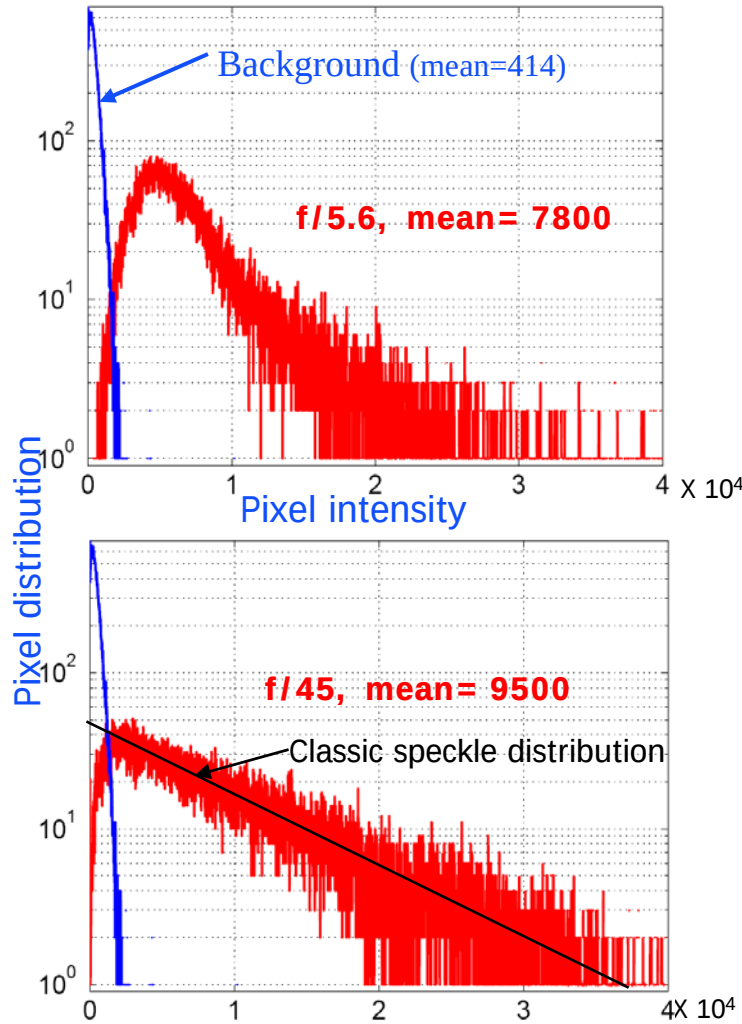
Beam center



f/45

Expect:
(mean $I_{speckle}$)/($I_{Defect\ Pts}$) = (f/#)²

Thus "defect points" disappear
Into speckle background



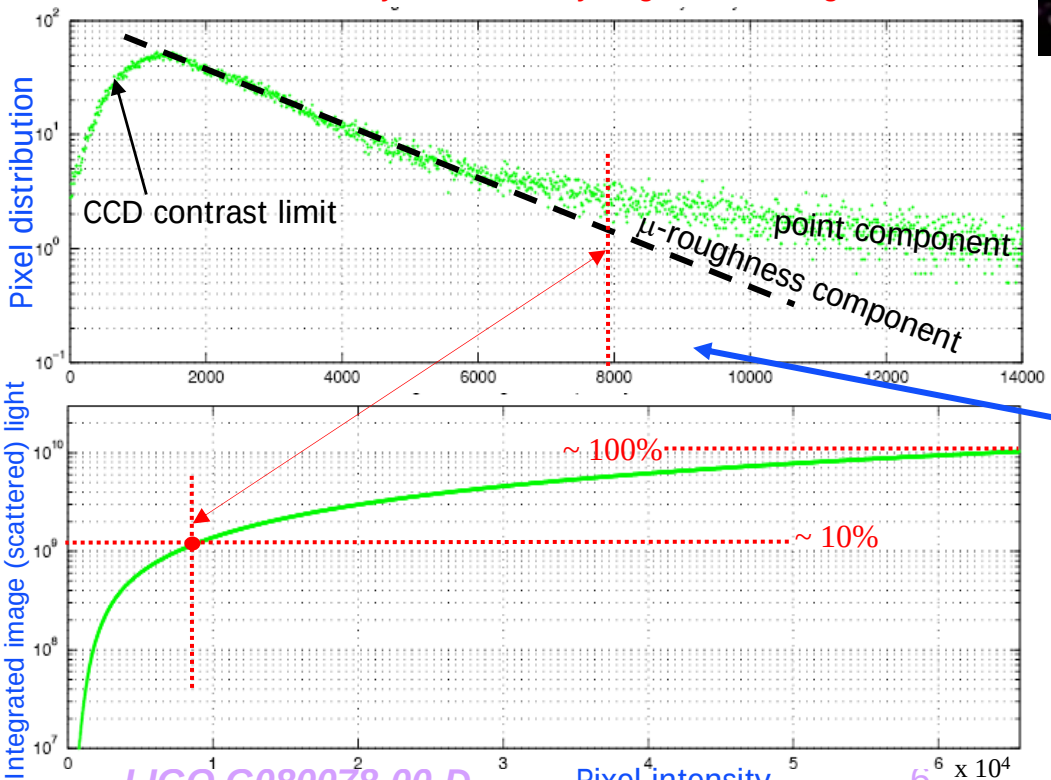
Improved resolution brings out “point” defects

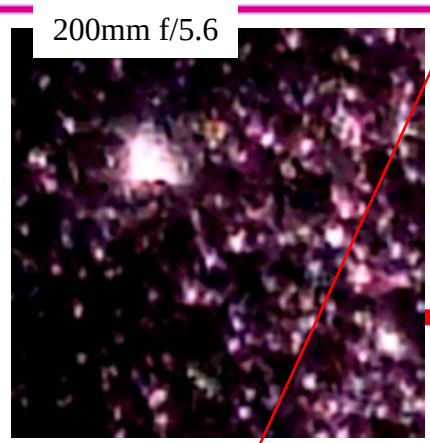
Post S5 LHO scatterometer survey included
a few updated photo sessions with even higher resolution
to conclusively distinguish localized point component.

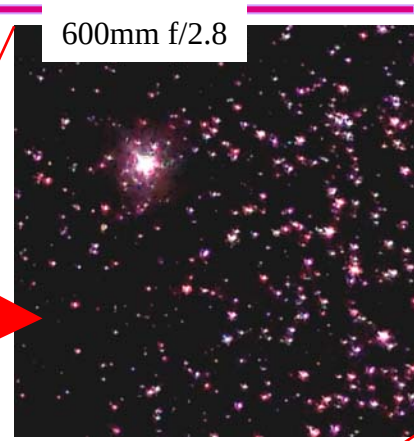
Re-imaged 2k ETMx showed same points, >3 years later.

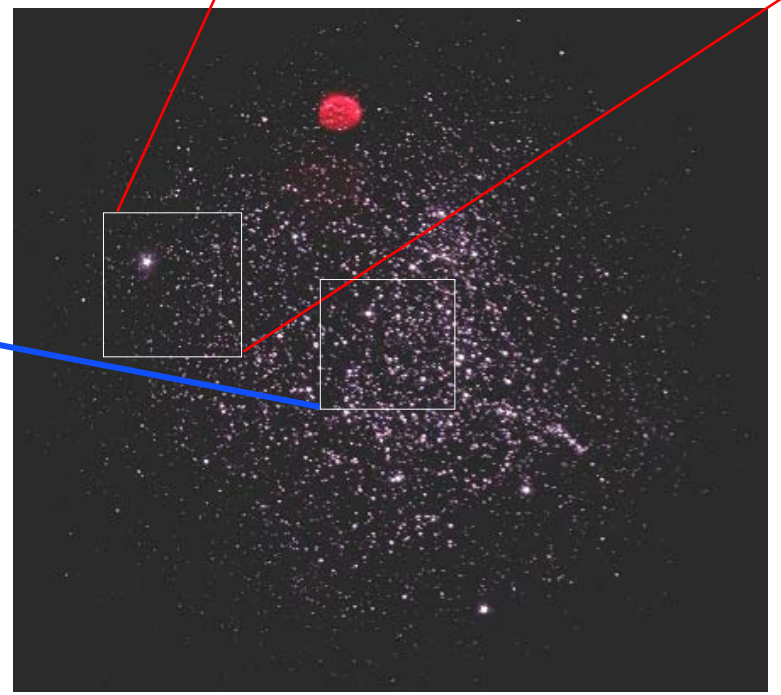
Preliminary quantitative result: point component loss ~90%
not inconsistent with scatterometer (slide 3) inference

However this at only one relatively large scatter angle !









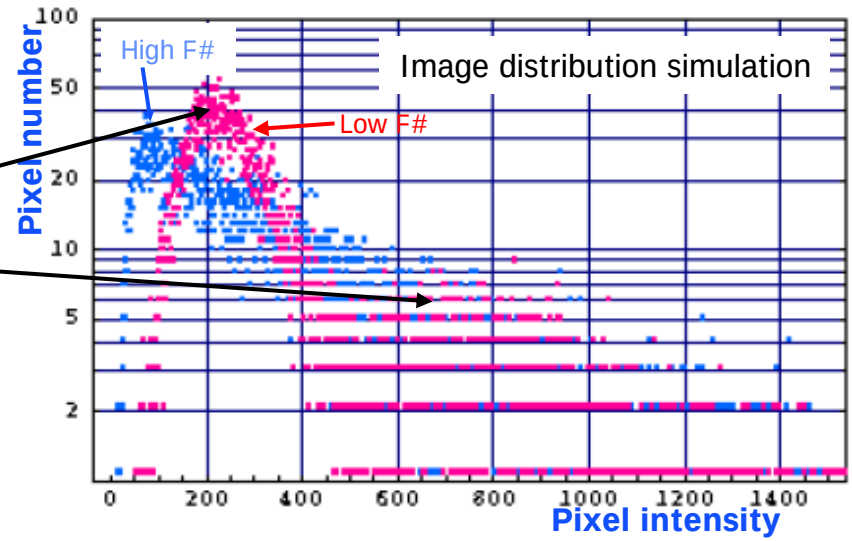
Background Speckle vs defects

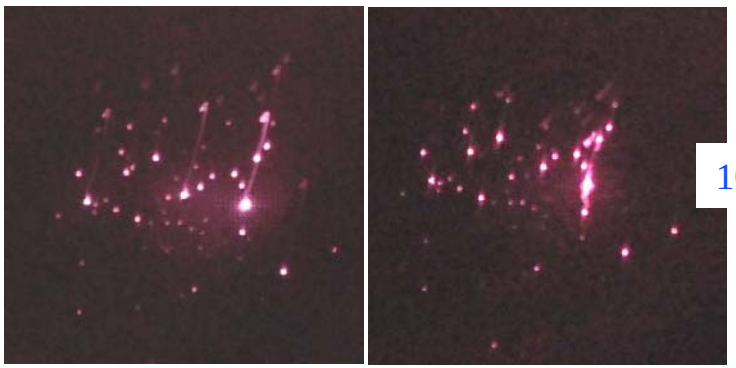
- Separate out “bright defect” tail of distribution via f/#.

Model of image distribution:

Background speckle component

Sporadic “point component”



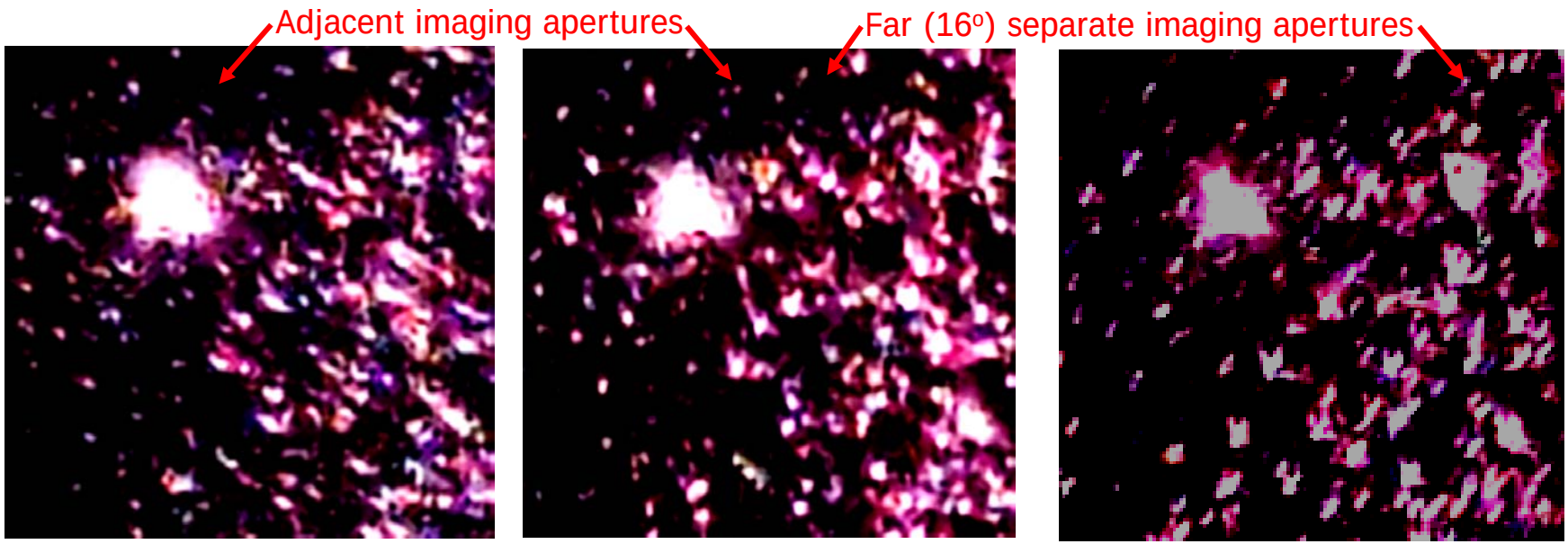


w~ 4 mm beam spot image in air.
Single pass reflection (no cavity)

- Speckle image pattern changes randomly with:
  - » Airy patch sample (~f/#)
  - » Different field solid angle patch (Δ camera view angle >.005 rad, LHO ETMs)
- Distinct (*within single Airy patch*) “point” defects remain fixed.
  - » Find: most bright points fixed (LIGO, 40m)

Image view point correlation

- For diffraction limited imaging, non overlapping apertures image random m-roughness speckle randomly differently.
- Brightest points in images (selected by contrast and f/# optimization) are fixed: violate random speckle aperturing.
- 2^D image overlay correlation software will make quantitative



Defects vs Speckle: Twinkling Images

- Cavity field illuminating HR surface: a **standing wave**
  - » For cavity end mirrors nodes exactly locked to TM position: **stationary images**

can (and do !) move wrt. field nodes: *image twinkling*

- Folding or splitter mirrors
  - ➢ ~ half pendulum period.
  - ➢ Full extinction can resolve $\lambda/2$

Micro scale defects ~full on/off and maintain fixed apparent image position.

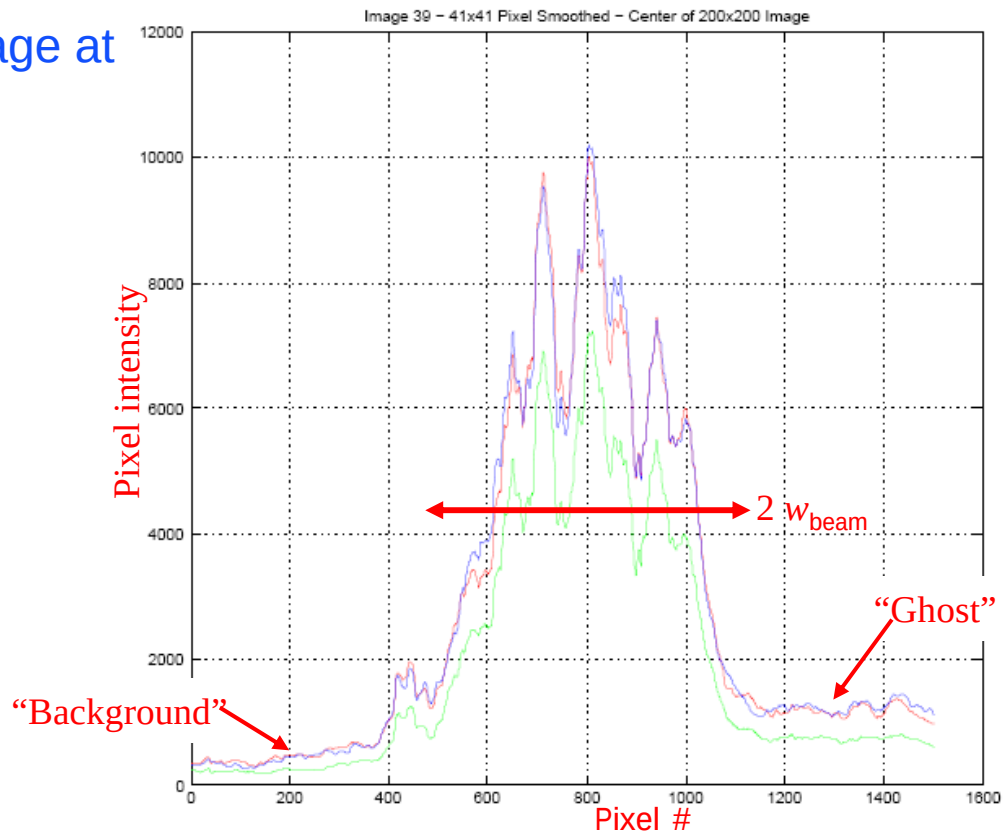
- Roughness speckle comes from random Avg. over Airy patch (>10^2 nodes wide):

Expect random Morphing wrt. node grating slewing

Irregularity of images confirmed

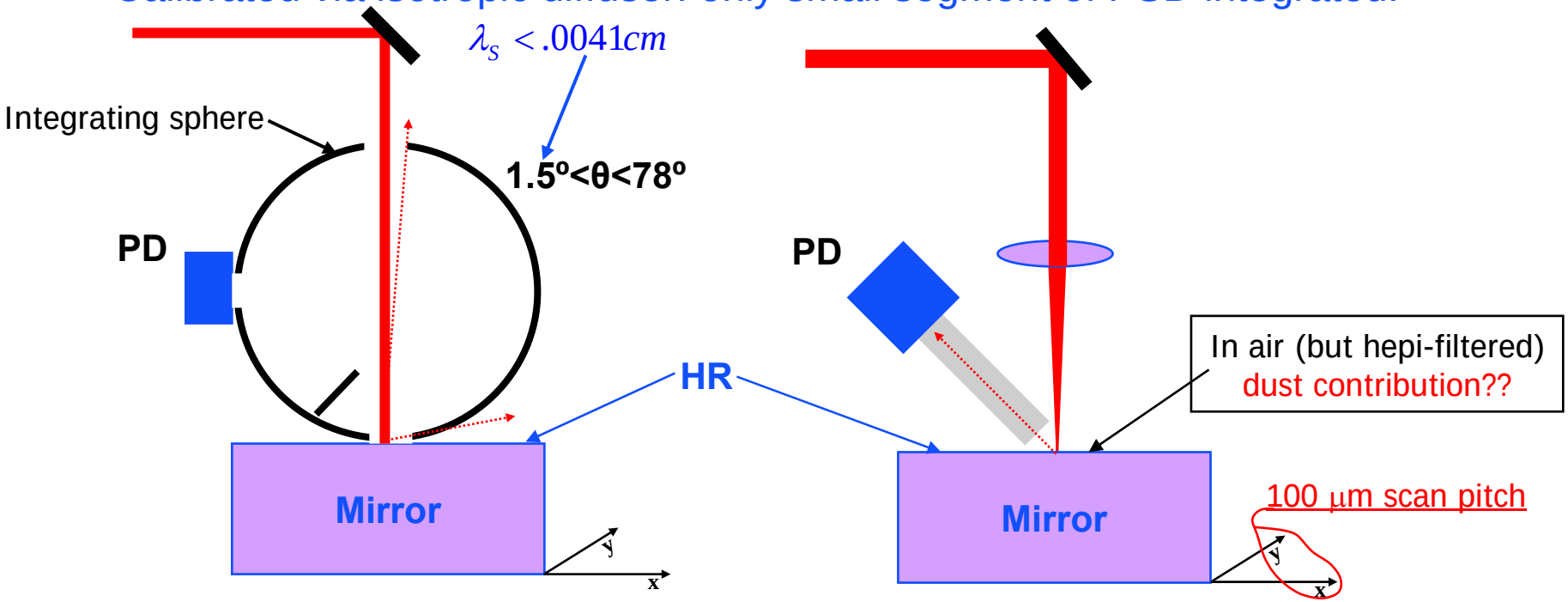
- Attempt to “smooth” image: reveal Gaussian profile
  - » Single pixel line through beam center
  - » Irregular on all scales
  - » Anomalous ghost [speckle] image at RH edge of beam spot

- Indicates in situ images have complex “dark” background dependence



Bench scatter mapping

- In air scanning of HR surfaces: scatter & absorb.
  - » Calibrated via isotropic diffuser: only small segment of PSD integrated.

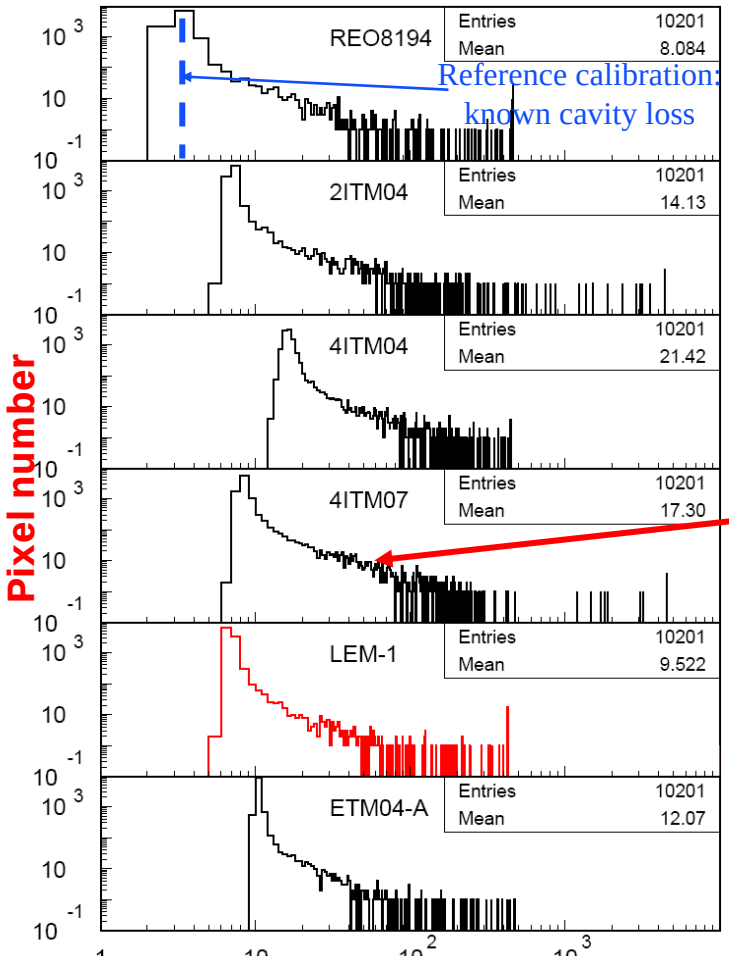


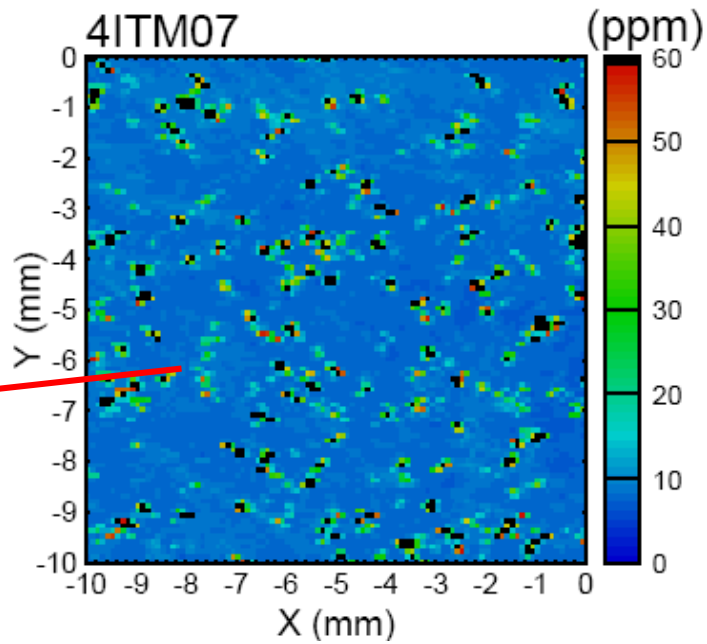
TIS: collimated beam, Dia.~.25 mm, modest spatial resolution, more collected scattering light.

BRDF @ 45 degrees: focused beam, Dia. 0.1 ~ 0.5 mm, high spatial resolution, less collected scattering light.

Homogeneous roughness ?

- Non-imaged scatter: many localized “defects”
  - » Min. background “micro-roughness” larger than PSD prediction.





TIS signal calibrated as ppm loss

Future outlook

- Higher than anticipated “point defect scatter”
  - » Contamination ? Is it dust (becoming clear mostly not)
  - » Better [coating] process control !
  - » Can contribute 10-20 ppm excess loss/mirror

- Polish finish
  - » Full use of “superpolish” technology: micro-roughness component < 1ppm
  - » Can substrates be polished significantly smoother on mm – cm scales
    - – This regime currently costs > 20ppm loss/mirror
  - » Possible goal HR mirrors with net loss (LIGO regime: long cavity, wide beam) <10ppm ???